A Transboundary Operating Model for Northeast Pacific Sablefish

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This document describes the Operating Model (OM) developed for use in a Management Strategy Evaluation (MSE) for northeast Pacific Sablefish, *Anoplopoma fimbria*. The OM is coded in R (R Core Team, 2019)(R Core Team, 2019) and Template Model Builder (Kristensen et al., 2016), and many elements are similar in structure to the widely-used statistical catch-at-age modeling software Stock Synthesis (Methot and Wetzel, 2013). The modeling framework was designed to represent several spatial areas, with movement occurring between spatial areas. The following sections describe the equations used to represent the population and fishery dynamics, and to condition the operating model.

Basic Operating Model Features

The operating model is age-structured, two-sex, and has an annual timestep (*y*). The plus-group age *A* for the model is 95 years; numbers- and biomass-at-age greater than age *A* are collapsed into this terminal group. Growth and selectivity are constant after this age. Here we provide a general description of the model dynamics through time. In this document, modeled spatial areas, termed sub-areas, are the union of biological stocks and political management regions (Figure 1). The biological stocks are defined by distinct demographic regimes, with growth described by Kapur et al. (2020) [cite maturity & movement when ready]. Sub-areas corresponding to the Alaskan Federal management regime are labelled "A"; sub-areas corresponding to British Columbia are labelled "B" and those off the West Coast of the United States/California Current labelled "C". In equations, sub-areas are indexed using the letters *i* and *j*, stocks using the letter *k,* and management regions using the letter *m.*

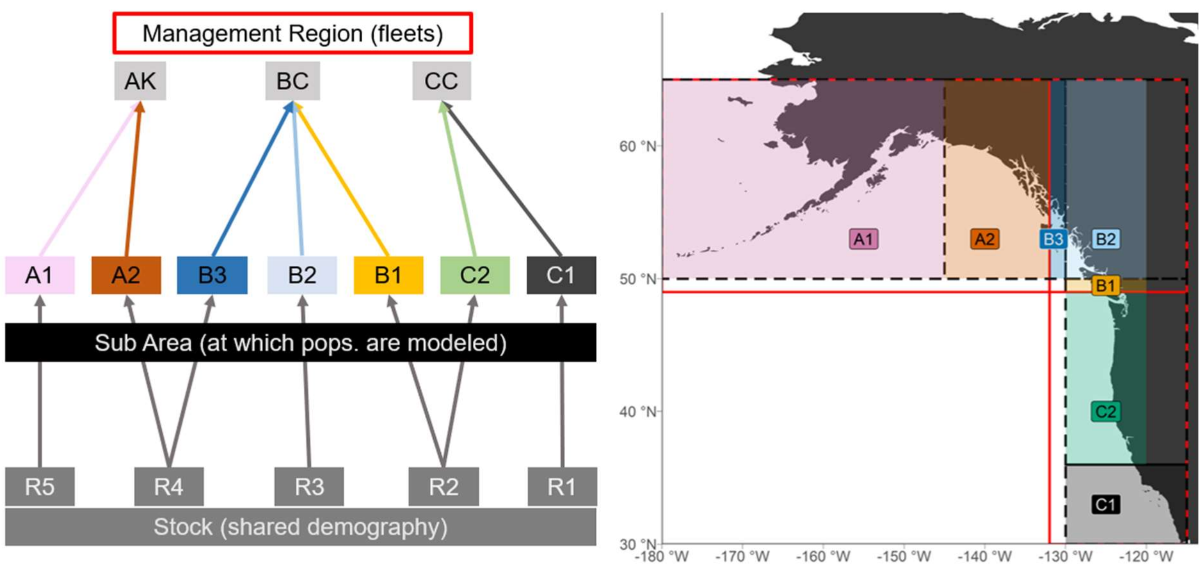

Figure 1. (Left) Schematic of biological area nesting within management regions. Biological areas (dark grey boxes) define the demographic regime within sub-areas (colored boxes), each of which corresponds to one of three management regions (light grey boxes), i.e., Alaska (AK), British Columbia (BC) or the California Current (CC). Colored arrows designate the sub-areas from which fish are surveyed and/or captured by fleets belonging to each management region. (Right) Map of spatial strata used in the operating model (shaded rectangles with labels). The red boxes delineate the current management regions. Stocks are demographically distinct, and there is movement between sub-areas as described in Rogers et al. (20xx).

Population Dynamics (Numbers at Age)

The basic dynamics of fish of sex γ in year y at age a within sub-area i are given by:

$$N^i_{y+1,\gamma,a} = \begin{cases} 0.5R^i_{y+1} & if\ a = 0 \\ \sum_{i\neq j}\left[\left(1-\boldsymbol{X}^{i,j}_a\right)N^i_{y,\gamma,a-1}e^{-Z^i_{y,\gamma,a-1}} + \boldsymbol{X}^{j,i}_a N^j_{y,\gamma,a-1}e^{-Z^i_{y,\gamma,a-1}}\right] & if\ 1 \leq a < A \\ \sum_{i\neq j}\left[\left(1-\boldsymbol{X}^{i,j}_a\right)\left(N^i_{y,\gamma,A-1}e^{-Z^i_{y,\gamma,A-1}} + N^i_{y,\gamma,A-1}e^{-Z^i_{y,\gamma,A-1}}\right)\right. & if\ a = A \\ \left. \ldots + \boldsymbol{X}^{j,i}_a\left(N^j_{y,\gamma,A}e^{-Z^j_{y,\gamma,A}} + N^j_{y,\gamma,A-1}e^{-Z^j_{y,\gamma,A-1}}\right)\right] & \end{cases} \quad (1)$$

where $N^i_{y,\gamma,a}$ is the number of animals of age a and sex γ in sub-area i at the start of year y;

$\boldsymbol{X}^{i,j}_a$ is the matrix of movement probabilities from sub-area i to sub-area j;

$Z^i_{y,\gamma,a}$ is the total mortality experienced in sub-area i during year y for animals of age a given fishery mortality and stock-, sex- and age-specific natural mortality $M^k_{a,\gamma}$. See section on Catches for more detail on how total mortality is calculated;

R^i_y is the number of recruits to sub area i at the start of year y (see section on Reproduction); and

A is the maximum age (treated as a plus-group).

The model operates on a yearly timestep, with the number of age-0 recruits by sex defined as half of the annual recruitment in each sub-area. For ages 1 through the plus-group, the number of individuals in sub-area i of sex γ and age a at the start of the next year is the sum of individuals in sub-area i that survive and do not emigrate, or immigrate into sub-area i after surviving year y within another sub-area j. The plus group in sub-area i is comprised of individuals who age into or remain at age A in sub-area i, plus individuals who age into or remain at age A in sub-area j and move into i.

Growth

Length-at-age is stock- and sex-specific and follows a von Bertalanffy growth function (Bertalanffy, 1938), which is incremented for each timestep y. The incremental setup prohibits fish from shrinking if they move into a sub-area corresponding to a stock with a lower L_∞, because the growth increment is a function of the difference between current size and asymptotic size in the stock at hand. However, because fish are able to move between sub-areas with different growth patterns throughout their lifetime, there is a possibility that the mean length-at-age could decline in a given sub-area should a large influx of smaller-at-age fish enter (see below). We present the growth equations indexed to sub-area i though note that sub-areas nested within the same stock k share growth patterns. The mean length-at-age a at the start of year y for sex γ in sub-area i is given by:

$$L^i_{y+1,\gamma,a} = L^i_{y,\gamma,a} + \left(L^i_{\infty,\gamma} - L^i_{y,\gamma,a}\right)\left(1 - e^{-\kappa^i_\gamma}\right)\ if\ a < A \quad (2)$$

For the plus group (age A) the mean size at the start of year y is calculated as the weighted average of fish entering and remaining in the plus-group within the sub-area. This calculation is based on the mean length-at-age in the middle of the (preceding) year. This setup allows the size of fish in the plus group to reflect changes (i.e. declines) due to exploitation and/or natural mortality (Methot & Wetzel, 2013).

$$L^i_{y+1,\gamma,A} = \frac{N^i_{y+1,\gamma,A-1}\widetilde{L^i_{y,\gamma,A}} + N^i_{y+1,\gamma,A}\left[L^i_{y,\gamma,a} + \left(L^i_{\infty,\gamma} - L^i_{y,\gamma,a}\right)\left(1 - e^{-\kappa^i_\gamma}\right)\right]}{N^i_{y+1,\gamma,A} + N^i_{y+1,\gamma,A-1}} \quad (3)$$

Where $\widetilde{L^{i}_{y,\gamma,a}}$ is the mean length-at-age at age a of sex γ in stock k at the midpoint of year y:

$$\widetilde{L^{i}_{y,\gamma,a}} = L^{i}_{y,\gamma,a} + (L^{i}_{\infty,\gamma} - L^{i}_{y,\gamma,a})\left(1 - e^{-0.5\kappa^{i}_{\gamma}}\right) \tag{4}$$

$L^{i}_{\infty,\gamma}$ is the stock and sex-specific asymptotic length (cm) for sub-area i; and

κ^{i}_{γ} is the stock and sex-specific growth rate (cm yr^{-1}) for sub-area i.

Unlike Stock Synthesis, all individuals present in a sub-area are subject to the growth pattern of the stock associated with that sub-area. This enables the modeling of ecosystem-based effects on the growth process, where a fish born in a southerly (slow-growing) region may grow to a greater size than expected based on its birth location if it moves to a northerly (fast-growing) region, and vice-versa.

Upon movement from one stock to another, the mean size of fish in the recipient sub-area becomes the weighted average of fish length-at-age already in the sub area and the length-at-age of fish entering the sub-area from a different sub-area *and* stock, both at the midpoint of the previous year. In subsequent years, fish residing in sub-area i are subject to the same movement probabilities regardless of their natal sub-area; the growth pattern of recruits is not tracked nor fixed throughout their lives. This calculation takes place after the calculation of the mean size of the plus group (Equation 333) and therefore applies to all ages.

$$L^{i}_{y+1,\gamma,a} = \phi_{ij}\frac{N^{i}_{y+1,\gamma,a}L^{i}_{y,\gamma,a} + N^{j}_{y+1,\gamma,A}L^{j}_{y,\gamma,a}}{N^{i}_{y+1,\gamma,a} + N^{j}_{y+1,\gamma,a}} \tag{5}$$

where ϕ_{ij} is a square array of i x i dimensions, indicating whether the new subarea j indeed belongs to a different stock than the source subarea k; ϕ_{ij} is 1 if the source and sink stocks for sub-areas i and j are distinct, and null otherwise. This structure means that if individuals move among sub-areas but not between *stocks* (which have distinct growth patterns), the weighted average is not calculated, and the sub-area retains the length-at-age values calculated in Equations 2-4.

$$\phi^{i}_{j} = \begin{cases} \begin{array}{cccccccc} & A1 & A2 & B3 & B2 & B1 & C2 & C1 \\ A1 & \oslash & 1 & 1 & 1 & 1 & 1 & 1 \\ A2 & 1 & \oslash & \oslash & 1 & 1 & 1 & 1 \\ B3 & 1 & \oslash & \oslash & 1 & 1 & 1 & 1 \\ B2 & 1 & 1 & 1 & \oslash & 1 & 1 & 1 \\ B1 & 1 & 1 & 1 & 1 & \oslash & \oslash & 1 \\ C2 & 1 & 1 & 1 & 1 & \oslash & \oslash & 1 \\ C1 & 1 & 1 & 1 & 1 & 1 & 1 & \oslash \end{array} \end{cases} \tag{6}$$

The growth module generates a stock- and sex-specific matrix $\widetilde{\boldsymbol{L}}$ which defines the annual probability of being in each of l length bins at age a in the middle of the year. The mean length-at-age a for sex γ in sub-area i at the midpoint of the year, $\widetilde{L^{i}_{y,\gamma,a}}$, is used as an approximation to size-at-age for any samples collected during the year.

$$\widetilde{\boldsymbol{L}^{i}_{y,\gamma,a,l}} = \begin{cases} \Phi(\theta_1, \widetilde{L^{i}_{y,\gamma,a}}, \sigma^{i}_{y,\gamma}) & if\ l = 1 \\ \Phi(\theta_{l+1}, \widetilde{L^{i}_{y,\gamma,a}}, \sigma^{i}_{y,\gamma}) - \Phi(\theta_l, \widetilde{L^{i}_{y,\gamma,a}}, \sigma^{i}_{y,\gamma}) & if\ 1 < l < A_l \\ 1 - \Phi(\theta_l, \widetilde{L^{i}_{y,\gamma,a}}, \sigma^{i}_{y,\gamma}) & if\ l = A_l \end{cases} \tag{7}$$

Similarly, the probability of being in each length bin at the start of year y is calculated using the length-at-age at the start of the year $L^{i}_{y,\gamma,a}$:

$$\boldsymbol{L}^i_{y,\gamma,a,l} = \begin{cases} \Phi(\theta_1, L^i_{y,\gamma,a}, \sigma^i_{G,y,\gamma}) & if\ l = 1 \\ \Phi(\theta_{l+1}, L^i_{y,\gamma,a}, \sigma^i_{G,y,\gamma}) - \Phi(\theta_l, L^i_{y,\gamma,a}, \sigma^i_{G,y,\gamma}) & if\ 1 < l < A_l \\ 1 - \Phi(\theta_l, L^i_{y,\gamma,a}, \sigma^i_{G,y,\gamma}) & if\ l = A_l \end{cases} \tag{8}$$

where Φ is the standard normal cumulative density function, which is evaluated for θ_l given a mean and standard deviation;
θ_l is the lower limit of length bin *l*;
A_l is the index of the largest length bin;
$\sigma^i_{G,y,\gamma}$ is the stock and sex-specific standard deviation of length at age, which is time blocked for some sexes (Table 3).

Specific values for the growth parameters are shared among sub-areas from the same stock as shown in Table 1. Body weight is converted from length via:

$$w^i_{\gamma,l} = \alpha^i_\gamma \overline{L_l}^{\beta^i_\gamma} \tag{9}$$

where α^i_γ and β^i_γ are stock- and sex- specific constants of the allometric length-weight equation; and
$\overline{L_l}$ is the midpoint of the population length bin.

The population-level body weight-at-age in a stock (or sub-area) at the start of the year is calculated using the stock- and sex-specific weight-at-age and the proportions at length at the start of the year:

$$w^k_{y,\gamma,a} = \sum_l \boldsymbol{L}^i_{y,\gamma,a,l} w^i_{\gamma,l} \tag{10}$$

The same calculation can be done using the mid-year stock- and sex-specific weight-at-age and proportions at length:

$$w^k_{y,\gamma,a} = \sum_l \tilde{\boldsymbol{L}}^i_{y,\gamma,a,l} w^i_{\gamma,l} \tag{11}$$

Reproduction

Recruitment follows a Beverton-Holt (1957) stock recruitment curve with annual deviations. Density-dependence is assumed to occur at the level of the stock (*k*) and is determined by the biomass (converted from numbers, as described above) of mature females in the stock, which may be the sum across two or more sub-areas, at the start of year *y*. The stock-recruitment relationship assumes that recruitment deviates occur at the stock level (and are thus equivalent among sub-areas within a stock).

$$R^k_y = \frac{4h^k R^k_0 S^k_y}{S^k_0(1-h) + S^k_y(5h-1)} e^{-0.5\sigma^2_R + \tilde{R}^k_y} \tag{12}$$

where h^k is the steepness of the stock recruitment curve (expected proportion of R0 at 0.2S0) for stock k;
R^k_0 is the virgin recruitment for stock k;
$\tilde{R}^k_y$ are random annual recruitment deviations specific to stock *k* and assumed to be normally distributed with mean zero and standard deviation σ_R;
S^k_y is the spawning biomass (mature females) in stock *k* at the start of year *y*. Recall that there is never more than one stock *k* in a sub-area *i:*

$S\_y^k =\sum\_\{a\}\{\phi\_\{ik\}N\_\{y,\gamma = female, a\}^iw\_\{y,\gamma = female, a\}^kE\_a^k\ \}$

(13)

ϕ_{ik} is a matrix indicating set to 1 if sub-area i is nested within stock k, and 0 otherwise;

$$\phi_{ik} = \begin{cases} & R1 & R2 & R3 & R4 & R5 \\ A1 & 0 & 0 & 0 & 0 & 1 \\ A2 & 0 & 0 & 0 & 1 & 0 \\ B3 & 0 & 0 & 0 & 1 & 0 \\ B2 & 0 & 0 & 1 & 0 & 0 \\ B1 & 0 & 1 & 0 & 0 & 0 \\ C2 & 0 & 1 & 0 & 0 & 0 \\ C1 & 1 & 0 & 0 & 0 & 0 \end{cases} \tag{14}$$

E_a^k is the proportion of females at age in stock k that have reached maturity at age a OR the fecundity at age, which is the integral over the length of the product of weight-at-length (like the weight equation, but instead of averaging over weight-at-length we average over proportion mature-at-length); and

S_0^k is the unfished female spawning biomass of stock k.

Recruits are allocated from stock k to sub-area i based on a fixed proportion. The resulting annual recruitment spawned within each sub-area is used in Equation 1.

$$R_y^i = \tau_{ik} R_y^k \tag{15}$$

Where τ_{ik} is a user-defined matrix specifying the distribution of recruits from stock k to sub-area i.

Fleets

A fleet is a discrete survey or fishing operation. There are several fleets *f* in each management region *m*, and there may be more than one fleet operating in each sub-area (Figure 2). All management regions have coverage by at least one fishery fleet or survey, and have length- or age-composition data from one or more fleets. Temporal coverage varies by management region, with catch records extending back to the early 1900s for Alaska and the California Current (Table 1). The Operating Model's main period, however, starts in 19XX.

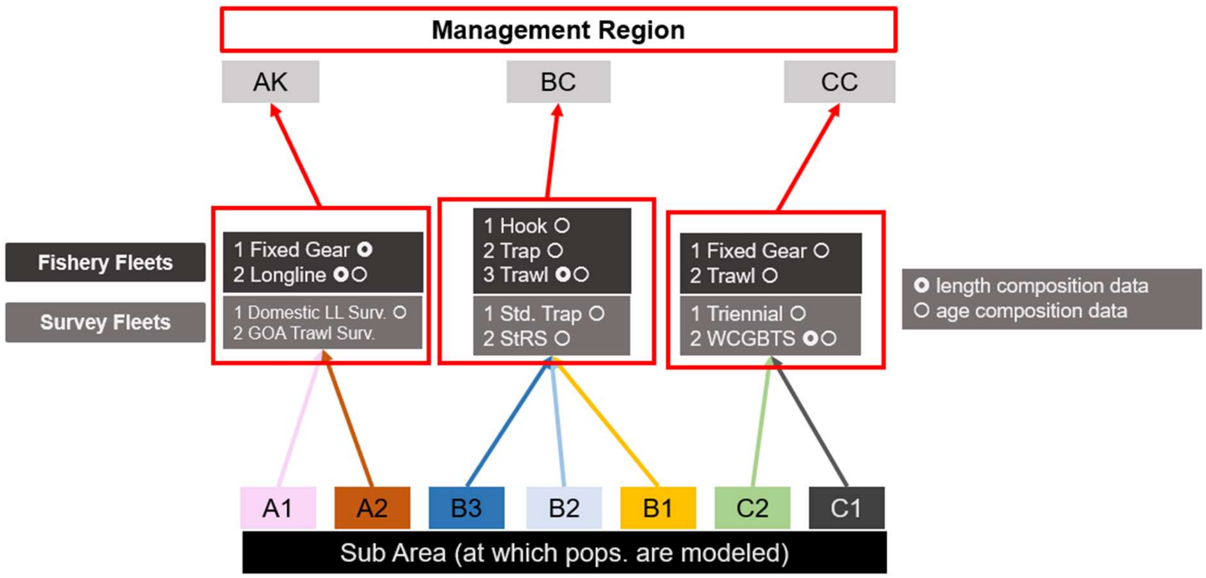

Figure 2. Schematic of available survey fleets (light grey boxes) fishery fleets (dark grey boxes) and associated compositional data (circular symbols) available for each of three management regions (lightest grey boxes at top). The sub-areas are fished/sampled by the fleets to which colored arrows point. Note that indices of relative abundance were re-created using a spatio-temporal model that reduced the number of survey fleets for several regions; compositions were retained at original fleet resolution.

Catches

Catches accrue to one of three management regions, which are comprised of at least one sub-area *i.* The data used to condition and test this OM are aggregated at the fleet level *f*, which are nested within management regions *m* and may exploit more than one sub-area *i.*

Discards

Total fishing mortality reflects both retained fish (according to a retention function) and the fraction of catches that are discarded and assumed to die. Ω is a logistic function defining the fraction of retained catch of animals of age a, during year y for fishery fleet f and sex γ. The function for discarded catch is simply 1- Ω. The mortality of discarded catch may vary by the age of fish.

$$\Omega^{f}_{y,\gamma,a} = \beta_3^{y,f,\gamma,a}\left(1 + exp(-a - (\frac{\beta_1^{y,f,\gamma,a} + \beta_4^{y,f,\gamma,a}}{\beta_2^{y,f,\gamma,a}})\right)^{-1} \tag{16}$$

Where $\beta_1^{y,f,\gamma,a}$ is the age at the inflection point of the logistic retention function;

$\beta_2^{y,f,\gamma,a}$ is the slope at the point of inflection;

$\beta_3^{y,f,\gamma,a}$ asymptotic fraction retained (note that discards + retained must sum to 1); and
$\beta_4^{y,f,\gamma,a}$ is 0 for females and an arithmetic offset for male ages.

Retained Catch

Fleet- and age-specific fishery catch is modeled using the Baranov catch equation (Ricker, 1975). The annual retained catch for each fleet in each management region $C_y^{m,f}$ is obtained by summing the catches by fleet *f* across all sub-areas *i* which are both fished by fleet *f* and nested within management region *m.* No fleet fishes in more than one management region. The use of the Baranov equation ensures that the numbers-at-age in any given year are always greater than zero.

$$C_y^{m,f} = \sum_{i \epsilon m} \sum_\gamma \sum_a \phi_{if} w_{\gamma,a}^f \frac{s_{\gamma,a}^f F_y^f \Omega_{y,\gamma,a}^f}{Z_{y,\gamma,a}^i} N_{y,\gamma,a}^i (1 - e^{-Z_{y,\gamma,a}^i}) \tag{17}$$

Where ϕ_{if} is a matrix indicating whether fleet *f* occurs in sub-area *i* (ϕ_{if} is set to 1 if fleet *f* occurs in sub-area *i*, and 0 otherwise);

$w_{\gamma,a}^f$ is fleet- and sex- specific weight-at-age for captured fish (assumed equivalent for all sub-areas *i* fished by *f*);

$s_{\gamma,a}^f$ is the selectivity by fleet *f* for animals of age *a* and sex γ (see section on Selectivity);

F_y^f is the fishing mortality rate on fully recruited animals by fleet *f* during year *y* (described in more detail below)

$Z_{y,\gamma,a}^i$ is the natural and total fishing mortality enacted by all fleets on fish of sex γ and age *a* in sub-area *i* during year *y*. As in Equation 1, we assume that F_y^f is equivalent across sub-areas (i.e. the fishing mortality by fleet *f* in sub-area *i* is the same as the fishing mortality of fleet *f* by sub-area *j*)):

$$Z_{y,\gamma,a}^i = M_{\gamma,a}^i + \sum_f \phi_f^i \left(s_{\gamma,a}^f F_y^f \Omega_{y,\gamma,a}^f + s_{\gamma,a}^f (1 - \Omega_{y,\gamma,a}^f) F_y^f V^f\right) \tag{18}$$

V^f is the fleet-specific mortality rate of discarded fish; if set to zero, all discards are assumed to survive and only retained catches figure into total mortality.

Fishing Mortality

The annual fishing mortality enacted by each fleet F_y^f is determined using the "hybrid" method, which has been implemented in Stock Synthesis as well as other stock assessment packages. The premise behind the hybrid method arises from the fact that F_y^f cannot be solved for explicitly but would be computationally expensive to estimate. Instead, the method algorithmically tunes the continuous *F* values for each fleet until the observed catches by fleet (across one or more sub-areas, as necessary) are matched. This is preferable to the Pope's approximation, which is invoked to provide the starting values for the tuning algorithm. The steps in the hybrid approach are as follows.

1) Identify an initial guess $\tilde{F}_y^{f\,1}$ for the annual fishing mortality of each fleet *f*. This initial guess is the ratio of the fleet's observed catch during year *y* to the total exploitable biomass available to fleet *f* at the start of the year *y*. In the case where fleet *f* fishes more than one sub-area, the total exploitable

biomass (denominator) necessarily sums biomass from each sub-area i where fleet f is active. Therefore, the resultant $\tilde{F}_y^{f1}$ corresponds to the entirety of fleet f's exploitation:

$$\tilde{F}_y^{f1} = \frac{C_{obs,y}^f}{\sum_i \sum_\gamma \sum_a \phi_{if} w_{a,\gamma}^f s_{a,\gamma}^f N_{y,\gamma,a}^i + C_{obs,y}^f} \quad (19)$$

where C_{obs}^f is the observed catch (retained + discard) for fleet f.

2) This initial guess is modified to become the starting value F_y^{f1} following Pope's approximation:

$$F_y^{f1} = -ln\left(1 - \left[\tilde{F}_y^{f1}\left(\frac{1}{1+exp(30(\tilde{F}_y^{f1}-v)}\right) + v(1 - \left(\frac{1}{1+exp(30(\tilde{F}_y^{f1}-v)}\right)\right]\right) \quad (20)$$

where v controls the upper limit on F_y^{f1}, as $\tilde{F}_y^{f1} \to \infty, F_y^{f1} \to -ln(1-v)$. This was set to 0.95, which corresponds to $F_y^{f1} = 3.0$. In other words, harvest rates above 0.95 are converted to an F corresponding to a harvest rate close to 0.95.

3) Compute model-predicted catches for each fleet (following the same equation structure as .
4)

,
$$C_{pred,y}^f = \sum_i \sum_\gamma \sum_a \phi_{if} w_{\gamma,a}^f \frac{s_{\gamma,a}^f \Omega_{y,\gamma,a}^f F_y^{f1} + s_{\gamma,a}^f (1-\Omega_{y,\gamma,a}^f)\, F_y^{f1} V^f}{Z_{y,\gamma,a}^i} N_{y,\gamma,a}^i (1 - e^{-Z_{y,\gamma,a}^i}) \quad (21)$$

5) Compute an adjustment factor *Adj* that will be used to tune total mortality. *Adj* is calculated using the ratio of the sums of observed and predicted catches from all fleets f operating within sub-area i:

$$Adj_y^i = \sum_f \phi_{if} \frac{C_{obs,y}^f}{C_{pred,y}^f} \quad (22)$$

6) Re-scale total mortality in the sub-area using Adj_y^i and the extant guess for fishing mortality:

$$\tilde{Z}_{y,\gamma,a}^i = M_{\gamma,a}^i + \sum_f \phi_{if} Adj_y^i (s_{\gamma,a}^f \Omega_{y,\gamma,a}^f F_y^{f1} + s_{\gamma,a}^f (1-\Omega_{y,\gamma,a}^f)\, F_y^{f1} V^f) \quad (23)$$

7) For the next iteration, the value of F_f is given by updating C_{pred}^f (Equation 20) with the new $\tilde{Z}_{y,\gamma,a}^i$ and repeating steps 2-4. The new F_f "guess" represents the ratio between the observed catches for fleet f and total exploitable biomass available to fleet f, given the adjusted value for total mortality found in Step 5.

,
$$\widetilde{F_y^{f2}} = \frac{C_{obs}^f}{\sum_i \sum_\gamma \sum_a \phi_{if} w_{\gamma,a}^f \frac{s_{\gamma,a}^f \Omega_{y,\gamma,a}^f F_y^{f1} + s_{\gamma,a}^f (1-\Omega_{y,\gamma,a}^f)\, F_y^{f1} V^f}{\tilde{Z}_{y,\gamma,a}^i} N_{y,\gamma,a}^i (1-e^{-\tilde{Z}_{y,\gamma,a}^i})} \quad (24)$$

8) This $\widetilde{F_y^{f2}}$ is again modified following Equation 20, with the change that v is multiplied by *Fmax*, here set to 2. This ensures that as $\widetilde{F_y^{f2}}$ (or any subsequent iterations) approaches 0. 95Fmax, F_y^{f2} approaches Fmax.

,

$$F_y^{f2} = -ln\left(1-\left[\widetilde{F_y^{f2}}\left(\frac{1}{1+exp(30(\widetilde{F_y^{f2}}-vF_{max})}\right)+v(1-\left(\frac{1}{1+exp(30(\widetilde{F_y^{f2}}-vF_{max})}\right)\right]\right) \quad (25)$$

9) Steps 2-6 are repeated several times. The final iteration terminates with a value of F_y^f following Equation 252525(34, which is applicable to the entire exploitation activity of a given fleet across a management region.

Selectivity (in Fleets & Surveys)

Selectivity, or the preferential sampling of sablefish, is both age-and length-specific in the operating model. For fleets operating in AK and CC management regions, the length-based selectivity function is 1.0 for all fleets and lengths as these assessments have historically not modeled length-based selectivity for any fleet. Aside from this constant (fully-selected) setup, selectivity curves can follow

$$s_a^f = (1+e^{-(a-a_{50}^f)/\delta^f})^{-1} \quad (26)$$

Selex placeholder (27)

Selex placeholder (28)

a_{50}, δ are the parameters of the (logistic) selectivity ogive…

Movement

Movement between areas is modeled using a matrix **X**, which models the distribution of fish at age *a* in sub-area *i* at the time when the catch is removed/when the surveys are conducted. The rows of the matrix correspond to the modelled areas in Figure 1. the column headers correspond to the management regions which consists of up to *A* matrices with elements representing the proportion of fish at age *a* in area *i* which move to another area *j* at the time when the catch is removed / when the surveys are conducted. For simulations in which movement is "off", all off-diagonal values of **X** are set to zero and diagonal elements are set to one; Movement parameters were obtained by the analysis of several decades' tag-recapture data for sablefish (cite Luke), implemented here as a saturating function of age.

$$\boldsymbol{X}_a^{i,j} = \frac{\kappa^{i,j}}{1+e^{\left(-\lambda^{i,j}(a-a_{50})\right)}} \quad (29)$$

Where κ is the maximum movement rate

λ determines the slope towards the maximum

a_{50} is the age at 50% of maximum movement rate

Equilibrium Abundance

To initialize the model, we calculate the unfished age distribution at the stock level and partition into sub-areas based on the following.

$$N_{0,y,a}^i = \begin{cases} 0.5\omega_a^i \tau_{ik} R_0^k e^{-\Sigma_a M_a^k} & if\ a < A \\ \omega_a^i \frac{N_{y,A-1}^i e^{\Sigma_a M_a^k}}{1-e^{-M_a^k}} & if\ a = A \end{cases} \quad (30)$$

Where ω_a^i is the eigenvector of the movement transition matrix described in the Movement section, with an entry for each sub-area within each stock. The entry for age 0 is an estimated parameter; and

τ_{ik} is a user-defined matrix specifying the distribution of recruits in stock k to sub-area *i*.

XX is an estimated variance term on τ_{ik}.

The unfished spawning biomass implements a 50:50 sex ratio:

$$S_0^k = 0.5 \sum_a R_0^k e^{-M_a^k} w_{\gamma=female,a}^k \tag{31}$$

Initial Conditions

The model is initialized with A years (denoted "init") of movement, recruitment deviations, and without fishing:

$$N_{init,y,a}^i = \begin{cases} 0.5\omega_a^i \tau_{ik} R_0^k e^{-\sum_a M_a^k} e^{-0.5\sigma_R^2 + \tilde{R}_{init-1}^k} & if\ a < A \\ \omega_a^i \frac{N_{init-1,y,A-1}^i e^{\sum_a M_a^k}}{1-e^{-M_a^k}} e^{-0.5\sigma_R^2 + \tilde{R}_{init-1}^k} & if\ a = A \end{cases} \tag{32}$$

Data Generation

Surveys – subscripts may change

Surveys occur at the start of the year. The operation of some survey fleets span more than one sub-area, in which case expected survey biomass B_y^f is computed as the sum across sub-areas (the assumption of homogeneity within stocks is held). For fleets that do not record the ages of surveyed fish, the a subscript on s is ignored.

$$B_y^f = \epsilon_y^f q^f \sum_i \sum_a \phi_{if} w_a^{k,f} s_a^f N_{y,a}^i \tag{33}$$

Where ϵ_y^f is the survey fleet- and year-specific error term, drawn from a lognormal distribution via the following. Observation error based on standard deviation in log-space of 0.2 (Francis, 2011) is added to a fleet-specific variance specific to survey years $\sigma_{S,y}^f$, calculated externally to the model:

$$\epsilon_y^f \sim lognormal(0, 0.2 + \sigma_{S,y}^f) \tag{34}$$

q^f is the catchability coefficient for survey fleet f;

ϕ_{if} is a matrix defining whether survey fleet f operates in sub-area i; and

s_a^f is the electivity for survey fleet f, which may follow one of three functional forms (see below).

Age & Length Compositions

Fishery and survey age compositions π are generated per year for applicable fleets based on the landed catch. For the fisheries, the proportion of individuals at age in the catch for fleet f in year y is found by dividing the prevalence in catch at age by the total caught biomass at age. The same formula is followed for length compositions, if applicable.

$$\backslash pi\_\{y,a\}\hat{}f = \backslash\text{frac}\{C\_\{y,a\}\hat{}f\}\{\backslash sum\_\{a\}\ C\_\{y,a\}\hat{}f\} \tag{35}$$

Collapsing Surveys & Compositional Data

Some estimation methods required combining data over multiple sub-areas. Converting survey index information from individual fleets and years B_y^f into a single index is achieved using a summation across fleets among years:

$$B_y^{f'} = q^{f'} \sum_i \sum_\gamma \sum_a \phi_{if} s_a^f N_{y,a}^i w_{y,a}^f \tag{36}$$

To combine length- and/or age-compositions from multiple surveys, the fleet-specific proportions π_a^f are weighted by the total observed numbers at age in sub-areas exploited by fleet f in that year $\widetilde{N}_{y,\gamma,a}^i$, which is calculated within the OM. These weighted values are then summed across fleets for each year and divided by the total number observed in all sub-areas concerned, returning the proportions-at-age for a single survey combining multiple fleets.

$$\pi_{y,a}^{f'} = \frac{\sum_{f \epsilon f'} \sum_i \sum_\gamma \phi_{if} \pi_a^f \widetilde{N}_{y,\gamma,a}^i}{\sum_i \sum_\gamma \widetilde{N}_{y,\gamma,a}^i} \tag{37}$$

Reference Points

Reference points are calculated for each management region. The derivation of reference points, and projection of the model forward (for experimentation with various harvest control rules, for example) relies upon the fishery selectivity patterns and relative fishing intensity among fleets (F^f). The fully-selected fishing mortality corresponding to *MSY*, F_{MSY}, is defined as the instantaneous rate of fishing mortality at which yield is maximized, is obtained via the following. Since dynamics happen at the stock and/or sub-area level, summations are made as necessary to obtain reference points at the scale of management.

1) For each fleet within management region *m*, calculate the time-averaged selectivity $\widehat{s^f_{\gamma,a}}$ and biology (body weight-at-age $\widehat{w^f_{\gamma,a}}$), and the relative fishing intensity per fleet $\widehat{F^f}$.
2) Define recruitment in the management area as a function of *F*, based on the stock-recruitment relationship defined for the OM:

$$R^m = \frac{\sum_{k\epsilon m}\sum_{f\epsilon m}\sum_a \phi_{if}\,\widehat{F^f}N^i_{\gamma=female,a} - \sum_{k\epsilon m}\alpha^k}{\beta^k\sum_{k\epsilon m}\sum_{f\epsilon m}\sum_a \phi_{if}\,\widehat{F^f}N^i_{\gamma=female,a}} \tag{38}$$

Where $\alpha^k = S_0^k\left(\frac{1-h^k}{4h^k}\right)$;

$S_0^k = 0.5\sum_a R_0^k e^{-M_a^k}\,\widehat{w^f_{\gamma=female,a}}\,e^{-0.5\sigma_R^2+R_0^k}$; and

$\beta^k = \frac{5h^k-1}{4h^kR_0^k}$

3) Define yield-per-recruit for the entire management region, as a function of all fleets contained within the region and the biomass of sub-areas fished by those fleets. As this set-up aims to maximize yield, not total deaths, only retained catches are included:

$$\tilde{Y}^m = \sum_{f\epsilon m}\sum_\gamma\sum_a \phi_{if}\,\widehat{w^f_{a,\gamma}}\,\frac{\widehat{s^f_{\gamma,a}}\,\widehat{\Omega^f_{\gamma,a}}\,\widehat{F^f}}{Z^i_{\gamma,a}}N^i_{\gamma,a}\left(1-e^{-Z^i_{\gamma,a}}\right) \tag{39}$$

where $N^i_{a,\gamma}$ is the relative number of fish of sex γ and age *a* relative to the total number (both sexes) of age-zero fish, given *F*, in equilibrium:

$$N^i_{a,\gamma} = \begin{cases} 0.5 & if\ a = 0 \\ N^i_{a-1,\gamma}e^{-Z^i_{\gamma,a-1}} & if\ 0 < a < A \\ \frac{N^i_{a-1,\gamma}e^{-Z^i_{\gamma,A-1}}}{1-e^{-Z^i_{\gamma,A}}} & if\ a = A \end{cases} \tag{40}$$

$Z^i_{\gamma,a}$ is the total mortality present in sub-area *i*:

$$Z^i_{\gamma,a} = M^i_{\gamma,a} + \sum_f \phi^i_f\left(\widehat{s^f_{\gamma,a}}\Omega^f_{\gamma,a}\widehat{F^f} + \widehat{s^f_{\gamma,a}}\left(1-\Omega^f_{\gamma,a}\right)\widehat{F^f}V^f\right) \tag{41}$$

4) Define the "yield function" as the product of yield per recruit under fully-selected fishing mortality and recruitment:

$$Y^m = \tilde{Y}^m R^m \tag{42}$$

5) Solve for the level of *F* that, when multiplied by the relative fishing intensities found in Step 1, maximize the yield function, i.e.:

$$\left.\frac{dY^m}{dF^m}\right|_{F^m_{MSY}} = 0 \tag{43}$$

Model Projections (Forecasts)

Forward projection of the model beyond the period with data necessitates the following assumptions, which can be divided between process and observational components:

Observation Error in Forecasts

Catches and "observed" survey biomass for each fleet are fixed to the average of the previous five years. Observed length and/or age compositions are bootstrapped resampling from the previous five years for each fleet. Selectivity patterns for all fleets are identical to the terminal year of the simulation.

Process Error in Forecasts

[Bias adjustment on rec-devs = 0.5 for forecasted years, leading to a median SSB/SSB0 of approximately 1 – if implemented].
Any changes or randomizations to demography.

Operating Model Data Inputs and Treatment

Input parameters, estimation boundaries and data used in conditioning the OM are available in Tables. Below we describe the data sources for the OM and treatment thereof.

Demographic Parameters

The spatial structure of "stocks" (black lines, Figure 1) are based upon the growth analyses performed by Kapur et al. (2020), which identified five unique regions of sablefish growth corresponding to major oceanographic features. In brief, growth in the OM follows a latitudinal cline whereby sablefish obtain a higher asymptotic length L_∞ at more north-western locales (i.e. sub-areas A1 and A2). The OM also has a time block in growth for females for all but the most north-westerly sub-areas, following findings by Kapur et al. (2020) that significant differences in growth parameters are present in females in these sub-areas before and after 2010. The results presented in Kapur et al. (2020) were updated to re-estimate individual values for σ_G. [Overview movement & maturity].

Fleets and Catches

The available fleets and compositional data corresponding to each region are shown in Figure 2; coverage by sample size and year is shown in Figure 3.

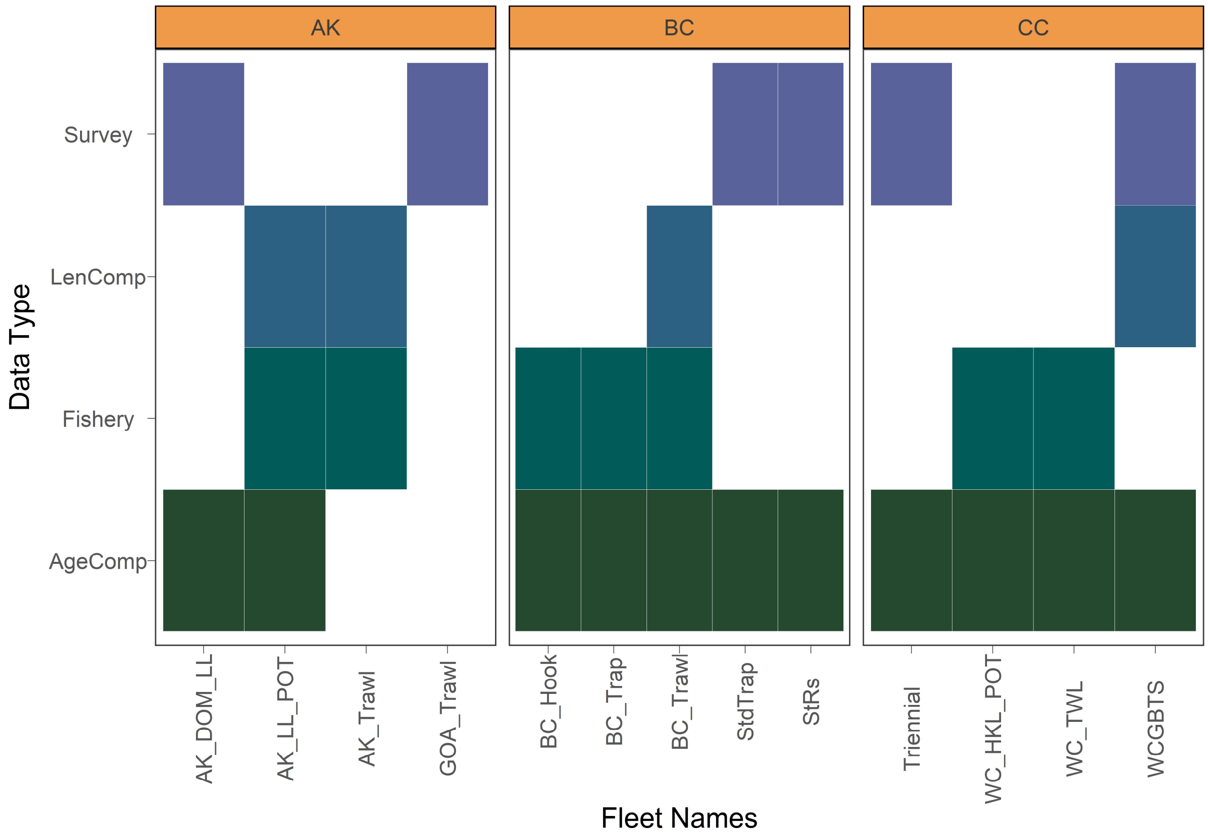

Figure 3. Plot of data available by source in Operating Model (Replace with SS_datplot mimic later). Available data is colored by data type and paneled by management region (AK = Alaska, BC = British Columbia, CC = US West Coast/California Current).

Fishery Catches

[Describe fishery fleets, and combination of fixed gears where appropriate]

Fishery Discards

The treatment of discarded catch varies by fleet and management region. For the CC, discard mortality is 20% for sablefish caught with fixed gear and 50% for sablefish captured with trawls, except for age-0 fish which were assumed to experience 100% discard mortality. [Discard mortality proportions by age are fixed for all regions].

Survey Fleets

We developed a new index of relative abundance using the Vectorized Auto-regressive Spatio-Temporal model (VAST, Thorson, 2019) which enabled the combination of various survey fleets into management-region specific indices (see Supplementary Material for full description of the modeling effort and findings). The indices were calibrated to roughly mimic the trend of individual indices used in separate assessment efforts. The index of relative abundance peaks for AK and the CC in the early 1990s, after which it declines substantially (Figure 4). The index for BC peaks in about 2004; indices for all management areas show slight increases since 2010.

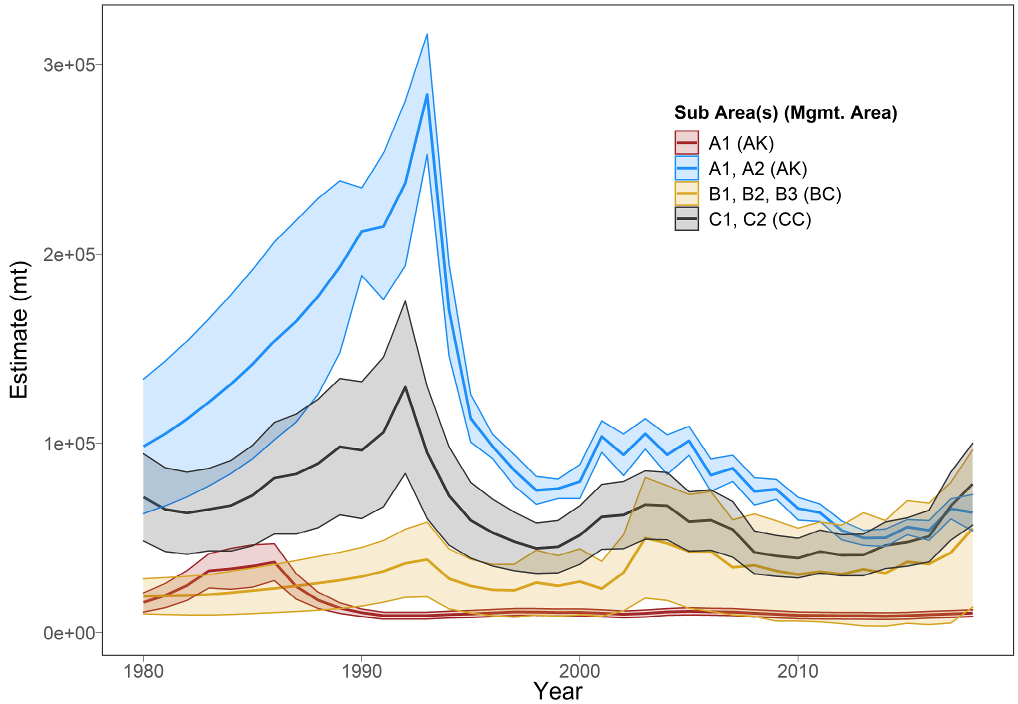

Figure 4. Indices of relative abundance developed for use in the operating model. Shaded intervals are 95% confidence intervals for estimated relative abundance in each management region. Colors correspond to the individual or collection of sub-areas surveyed by the index.

Compositional Data

[Describe comps and any treatment -- aging error, expansions, or weighting by catches]

Conditioning the Operating Model

Here, "conditioning" refers to the procedure undertaken to estimate and/or specify the parameters used in the Operating Model. As mentioned in the Demographic Parameters section, many model values concerning growth, movement and maturity were estimated externally and thus were not revisited in OM development (Table 2). The goal of this step was to find model outputs which roughly mimic reality (i.e. the general trend in spawning biomass observed from respective management regions in recent stock assessments). We do not expect model results or likelihoods to be identical to those for any current assessments, as the spatial nature of the OM, combined with the novel survey indices developed for this study, and the inclusion of movement render such comparisons unreasonable.

For this conditioning step, an estimation model (EM) which mimics the OM's structure and functional forms was developed in Template Model Builder (TMB**)**. The likelihood functions used in the maximum likelihood framework are described below, and are ordered to match the description of the OM.

Likelihood Components

This section provides an overview of the contribution to the objective function by data type. Table 2 specifies which form (e.g. normal, beta-distributed) is followed for each estimated parameter.

General parameters

The growth, fecundity, and movement parameters used in the Operating model were estimated externally, so the input parameters defining the expected distribution of length at age were fixed to those presented in Table 3. Generally the contribution to the objective function by parameters θ following a normal distribution is:

$$L_\theta = \frac{1}{2}\left(\frac{\theta - \mu_\theta}{\sigma_\theta}\right)^2 \tag{44}$$

Where μ_θ is the prior mean for the parameter; and

σ_θ is the standard deviation for the parameter prior.

The contribution for parameters θ following a lognormal distribution is:

$$L_\theta = \frac{1}{2}\left(\frac{ln(\theta) - \mu_\theta}{\sigma_\theta}\right)^2 \tag{45}$$

Steepness

Steepness for each stock h^k is estimated using a beta-distributed penalty on stock-specific deviations from a mean h. The contribution for each stock's steepness estimate to the objective function is:

$$\begin{aligned} L_{h^k} = -\sigma_h \Big(\Big[ln\left(\tfrac{1}{2}(h_{max} - h_{min}) - h_{min}\right) + ln(0.5)\Big] \\ \cdots + ln(h^k - h_{min} + 0.0001 \\ \cdots + ln\Big(1 - \frac{h^k - h_{min} - 0.0001}{h_{max} - h_{min}}\Big) \end{aligned} \tag{46}$$

For clarity, we can alternatively express Equation 46 as a beta-distribution with shape and rate parameters $\tau(1-\mu), \tau\mu$:

$$-log(L_h^k) = beta(h^k, \tau(1-\mu), \tau\mu) \tag{47}$$

where $\tau = \frac{\left((h^k - h_{min})(h_{max} - h^k)\right)}{\sigma_h^2} - 1$; and

$$\mu = \frac{\left(h_{prior} - h_{mini}\right)}{h_{maxi} - h_{mini}}$$

Recruitment Deviations

The recruitment deviations are assumed to be lognormally distributed.

$$L_{Rec} = \frac{1}{2}\left(\sum_y \frac{\widetilde{R_y^2}}{\sigma_R^2} + b_y \, ln(\sigma_r^2)\right) \quad (48)$$

[Describe penalty ramp if implemented]

Catch and Discards

Discards are assumed to follow a t-distribution, and accumulate on a per-fleet basis:

$$L_{Disc}^f = \frac{1}{2}(df^f + 1)ln\left[\frac{1 + \left(D_{obs,y}^f - D_{pred,y}^f\right)^2}{df^f \sigma_y^{2,f}}\right] \quad (49)$$

Where df^f is the degrees of freedom for fleet *f*;

$D_{obs,y}^f$ is the observed discard for year *y* by fleet *f*;

$D_{pred,y}^f$ is the predicted discard for year *y* by fleet *f* given by the following ($Z_{y,\gamma,a}^i$ in this case is the same as in Equation 17, considering total mortality);

$$D_{pred,y}^f = \sum_i \sum_\gamma \phi_{if} \frac{s_{\gamma,a}^f F_y^f (1 - \Omega_{y,\gamma,a}^f)}{Z_{y,\gamma,a}^i} N_{y,\gamma,a}^i (1 - e^{-Z_{y,\gamma,a}^i}) \quad (50)$$

σ_y^f is the standard deviation for discards for year *y* by fleet *f*.

Annual catches follow a lognormal distribution, with a very small standard deviation (0.01) to nearly fit catches without error.

$$L_{Catch} = \frac{1}{2}\left(\sum_y \frac{\left[ln(C_{obs,y}^f) - ln(C_{pred,y}^f)\right]^2}{0.01^2}\right) \quad (51)$$

Similarly, equilibrium catch contributes to the objective function via the following; where C_{pred0}^f is fixed/estimated.

$$L_{Catch\_Eq} = \frac{1}{2}\left(\frac{\left[ln(C_0^f) - ln(C_{pred0}^f)\right]^2}{0.01^2}\right) \quad (52)$$

Survey Biomass

Estimates of relative abundance (biomass) from each survey are fit following a lognormal distribution for each year *y* present in the survey timeseries for fleet *f*, which are equivalent across fleets:

$$L_{surv}^f = \sum_y \frac{(ln(B_{Obs,y}^f) - ln(q^f B_y^f))^2}{2\epsilon_y^{f^2}} + ln(\epsilon_y^f) \quad (53)$$

Recall that the adjusted standard deviation ϵ_y^f is a constant variance term plus a time-varying term calculated externally as a part of the kriging and extrapolation procedures within VAST (σ_y^f).

Compositional Data

Age- and length-composition data from both the survey and catches are fit using the linear parameterization of the Dirichlet-multinomial compound distribution (Thorson et al., 2017). The contribution of the composition dataset from fleet *f* in year *y* to the objective function is as follows (the same approach is used for length compositions, though age is shown here):

$$L_\pi^f = \frac{\Gamma(n_y^f+1)}{\prod_a^A \Gamma(n_y^f \Sigma_\gamma \widetilde{\pi_{y,\gamma,a}^f}+1)} \frac{\Gamma(\theta^f n_y^f)}{\Gamma(n_y^f+\theta^f n_y^f)} \prod_a^A \frac{\Gamma(n_y^f \Sigma_\gamma \widetilde{\pi_{y,\gamma,a}^f}+\theta^f n_y^f \Sigma_\gamma \pi_{y,\gamma,a}^f)}{\Gamma(\theta^f n_y^f \Sigma_\gamma \pi_{y,\gamma,a}^f)} \tag{54}$$

Where n_y^f is the total number of samples in the available data from fleet *f* in year *y* (for both sexes);

$\widetilde{\pi_{y,\gamma,a}}$ is the proportion at age in the dataset for fleet *f* in year y of sex γ which sum to 1;

$\pi_{y,\gamma,a}^f$ is the estimated proportion at age for fleet *f* in year y of sex γ, which also sum to 1,

θ^f is the estimated Dirichlet-Multinomial shape parameter pertaining to the compositions (age or length) from fleet *f*. The product of θ^f and n_y^f represents the overdispersion caused by the Dirichlet distribution. (Note that there is only one shape parameter estimated per fleet dataset).

The effective sample size is given by:

$$n_{effective,y}^f = \frac{1+\theta^f n_y^f}{1+\theta^f} \tag{55}$$

Tables

Region	Data Type	Description & handling notes	Reference
California Current	Landings	**2 Fleets (1990-present)**: Fixed gear (Hook & Line, and Pot), and Trawl	(Haltuch et al., 2019)
	Compositions	**Fishery-Dependent:** Ages from all fleets (via commercial port sampling) **Fishery-Independent:** Lengths & Ages from West Coast Groundfish Bottom Trawl Survey (2003-present) Ages from Triennial survey (1980-2004)	(Haltuch et al., 2019)
	Indices of Abundance	**Fishery-Dependent:** Commercial CPUE series have not been included in any recent sablefish stock assessment. **Fishery-Independent:** ●Both standardized using VAST: Triennial survey (1980-2004) and West Coast Groundfish Bottom Trawl Survey (2003-present) ⁑California Current Index of Relative Abundance (1980-2018)	(Haltuch et al., 2019)
British Columbia	Landings	**3 Fleets (1965-present):** Commercial longline trap, Longline hook, and Trawl	(Fenske et al., 2019)
	Compositions	**Fishery-Dependent:** Ages from the fishery, primarily the trap sector; lengths from commercial trawl **Fishery-Independent:** Ages from trap-based Standardized Survey (1991-2009); trap-based Stratified Random Survey (2003-present)	Fenske et al. (2019); (DFO, 2019)
	Indices of Abundance	**Fishery-Dependent**: nominal trap fishery CPUE (1979-2009) **Fishery-Independent:** ●Standardized trap-based Standardized Survey CPUE (1991-2009); trap-based Stratified Random Survey CPUE (2003-present) ⁑British Columbia Index of Relative Abundance (1980-2018)	Fenske et al. 2019
Alaska	Landings	**2 fleets (early 1900s-present; typically cut to 1970 onward):** Fixed-gear (longline & pot) and Trawl	Hanselman et al., 2019
	Compositions	**Fishery-Dependent:** Lengths (1990-present) and ages (1999-present) from Fixed-gear fishery; occasional lengths from trawl fishery **Fishery-Independent:** Ages from longline surveys (1979-present, with some collection variability)	
	Indices of Abundance	**Fishery-Dependent:** Filtered nominal CPUE scaled to area for longline fishery **Fishery-Independent:** ●Domestic Longline Survey (1979-present) and NMFS AFSC Gulf of Alaska Bottom Trawl Survey (1980-present). ⁑Gulf of Alaska Index of Relative Abundance (1980-2018) ⁑Aleutian Islands Index of Relative Abundance (1980-2018)	

Table 1. Input data available for inclusion in operating model(s). ●Original treatment of survey data (i.e. in recent stock assessments used for management). ⁑New index of relative abundance standardized using VAST, which combines survey(s) from this management region across space and time.

Symbol	Description	Operating Model Treatment	Estimated? [bounds]
Model Structure			
i	sub-areas	N = 7	
k	Stocks (shared demography)	N = 5	
m	management regions m	N = 3	
f	fishing fleets	N = 7 (2 – CC, 3 – BC, 2 – AK)	
f	survey fleets	N = 4 (1 per management region, 2 for AK)	
f	fishing fleets with composition data	Ages: N = 3 (1 per management region) Lengths: N = 2 (one each from AK, BC)	
f	survey fleets with composition data	Ages: N = 5 (2 – CC, 2 – BC, 1 – AK) Lengths: N = 3 (1 per management region)	
Growth*			
$M_{a,\gamma}^{k}$	Stock- and sex-specific natural mortality at age. (Note equations use sub-area indexing)		
$L_{\infty,\gamma}^{k}$	Asymptotic length (cm)	Sex, stock and year specific (Table 3)	no
κ_{γ}^{k}	Growth rate (cm yr^{-1})	Sex, stock and year specific (Table 3)	no
σ_G	Standard deviation for length at age (cm)	Sex, stock and year specific (Table 3)	no
α_{γ}^{k}	Coefficient of length-weight relationship (lbs/cm)	Sex and stock specific	
β_{γ}^{k}	Allometric exponent of length-weight relationship	Sex and stock specific	
Reproduction			
ϕ_{ik}	Matrix indicating whether sub-area i is nested within stock k	See Equation 14	
h^k	steepness of the stock recruitment curve (expected proportion of R_0 at $0.2S_0$) for stock k	Estimated from beta-distribution for each stock with min, max…	yes
E_a^k	proportion of females at age in stock k which have reached maturity at age a	See Table X	no
$\tilde{R}_y^k$	random annual recruitment deviations specific to stock k	normally distributed with mean zero and standard deviation σ_R	yes
b_y	Recdev penalty for data poor pds	Time-varying, see Table X	yes
σ_R	Standard deviation of recruitment deviations	log(1.4)	no
R_0^k	Unfished recruitment by stock		yes
Catches			
ϕ_{if}	Matrix indicating whether fleet f occurs in sub-area i		
$\beta_{1,2,3,4}^{y,f,\gamma,a/l}$	Age @ inflection point, slope @ inflection point, asymptotic selection and male offset for logistic retention curve	Either fleet specific, or regional by type	
$w_a^{k,f}$	stock- and fleet-specific weight-at-age of captured fish	See Table X	
a_{50}, δ	Fishery selectivity parameters placeholder	Fleet-specific, see Table 4	
Surveys			

σ_S	Annual standard deviation of relative abundance by fleet	See Table 5	no (estimated externally)
$w_a^{k,f}$	stock- and fleet-specific weight-at-age of sampled fish	See Table X	
a_{50}, δ	Survey selectivity parameters placeholder	Fleet-specific, see Table 4	
q^f	Survey catchability coefficient		yes
Age & Length Compositions			
π^f	Fleet- specific proportion at length or age; can be year- and/or gender-specific		
θ_a^f	Fleet-specific Dirichlet-Multinominal parameter		yes
	Aging error placeholder		
Movement			
$\boldsymbol{X}_a^{i,j}$	Sub-area age-based movement matrix	See Table X	no (estimated externally)
$\omega_a^{i,k}$	Eigenvector of $\boldsymbol{X}$		yes, for age-zero
τ_{ik}	Proportional distribution of recruits spawned in stock k to sub-area $i; i \varepsilon k$	See Table X	no
	Movement uncertainty or other movement placeholder		

Table 2. Overview of parameters used in operating model. Acronyms referring to OM-specific regions are explained in-text and depicted in Figure 1. *In text, growth equations use sub-area indexing (i) to clarify the expected length-at-age as fish move among sub-areas from different stocks. In practice, sub-areas belonging to the same stock k share growth patterns.

Region	Sex	Period	L_{∞}^{k} (cm)	κ_{γ}^{k} (cm yr^{-1})	σ^{k} (cm)
C1	Fem	<2010	60.3	0.29	4.98
C1	Fem	2010+	62.75	0.16	4.8
C1	Mal	All years	55.07	0.28	3.89
C2, B1	Fem	<2010	69.36	0.22	11.8
C2, B1	Fem	2010+	68.08	0.18	9.68
C2, B1	Mal	All years	59.02	0.21	7.16
B2	Fem	<2010	70.14	1.29	8.31
B2	Fem	2010+	72.5	0.43	12.36
B2	Mal	All years	61.67	0.46	9.35
A2, A3	Fem	<2010	74.71	0.65	8.32
A2, A3	Fem	2010+	75.58	0.33	10.43
A2, A3	Mal	All years	63.98	0.57	5.75
A1	Fem	All years	81.43	0.14	6.57
A1	Mal	All years	68.34	0.2	4.75

Table 3. Growth parameters used in Operating Model, adapted from Kapur et al. 2020.

Mgmt. Region	Fleet Name	Fleet Type	Years	Selectivity form
AK		Survey	1980-2018	
AK		Fishery (retained)		
		Fishery (discard)		

Table 4. Placeholder: Survey and fishery Fleets, years of available data, and form of selectivity curve.

Year	CC	BC	AK (sub-areas A1 + A2)	AK (sub-area A1)
1980	71499	19172	98336	15865
1981	64929	19310	105094	19505
1982	63062	19567	112813	24800
1983	64952	19931	121638	32543
1984	66970	20965	131094	33615
1985	72437	22079	141841	35180
1986	81598	23281	154072	37254
1987	83777	24602	164491	24307
1988	89275	26029	177531	17069
1989	98168	27573	193250	12939
1990	96380	29505	211854	10526
1991	105881	32313	214531	9012
1992	129615	36574	237396	8979
1993	95091	38621	284257	9031
1994	72296	28434	170503	9553
1995	59301	24587	113200	9882
1996	52819	22467	98413	10385

1997	48036	22237	85635	10903
1998	44516	26351	75088	10892
1999	45320	24664	75908	10657
2000	51524	26883	79760	10725
2001	61045	23161	103613	10256
2002	62093	31624	93956	9681
2003	67422	50025	105044	10135
2004	66858	47228	94018	10945
2005	58624	42894	101367	11276
2006	59380	42858	83131	11040
2007	54518	34490	86807	10867
2008	42372	35600	74568	10242
2009	40549	32579	75626	9716
2010	39359	30644	65422	9169
2011	42752	32094	63212	9039
2012	40901	30759	53988	8934
2013	41097	33435	50074	8891
2014	46112	31303	50144	8719
2015	47851	37355	55728	8982
2016	50927	36290	54041	9485
2017	66813	42228	65267	9858
2018	78406	55079	63330	10300

Table 5. Input standardized survey biomass, by management region. These were standardized using VAST. Note that for the Alaska management region, one of the surveys applies only to sub-area A1.

Year	CC	BC	AK (A1 + A2)	AK (A1)
1980	0.322	0.48	0.362	0.315
1981	0.341	0.502	0.365	0.325
1982	0.344	0.519	0.365	0.318
1983	0.335	0.533	0.363	0.279
1984	0.358	0.54	0.36	0.323
1985	0.366	0.543	0.352	0.319
1986	0.361	0.544	0.339	0.264
1987	0.377	0.545	0.323	0.278
1988	0.38	0.544	0.292	0.25
1989	0.367	0.539	0.235	0.212
1990	0.375	0.527	0.109	0.189
1991	0.374	0.506	0.18	0.197
1992	0.351	0.493	0.183	0.195
1993	0.366	0.512	0.112	0.193
1994	0.36	0.557	0.142	0.183
1995	0.336	0.576	0.111	0.185
1996	0.334	0.605	0.065	0.179

1997	0.321	0.629	0.097	0.168
1998	0.3	0.649	0.099	0.17
1999	0.306	0.65	0.068	0.174
2000	0.299	0.648	0.112	0.168
2001	0.28	0.625	0.08	0.177
2002	0.286	0.636	0.117	0.18
2003	0.268	0.637	0.076	0.178
2004	0.266	0.642	0.112	0.165
2005	0.267	0.701	0.076	0.167
2006	0.268	0.737	0.104	0.164
2007	0.269	0.728	0.081	0.173
2008	0.268	0.759	0.098	0.179
2009	0.268	0.812	0.07	0.185
2010	0.267	0.8	0.091	0.189
2011	0.267	0.822	0.072	0.193
2012	0.268	0.844	0.092	0.192
2013	0.269	0.892	0.078	0.195
2014	0.267	0.892	0.091	0.196
2015	0.267	0.866	0.07	0.194
2016	0.267	0.883	0.096	0.183
2017	0.269	0.879	0.081	0.182
2018	0.276	0.755	0.152	0.174

Table 6. Input standardized survey log standard deviations (σ_S^2), by management region. These were standardized using VAST. Note that for the Alaska management region, one of the surveys applies only to sub-area A1.

Additional Figures

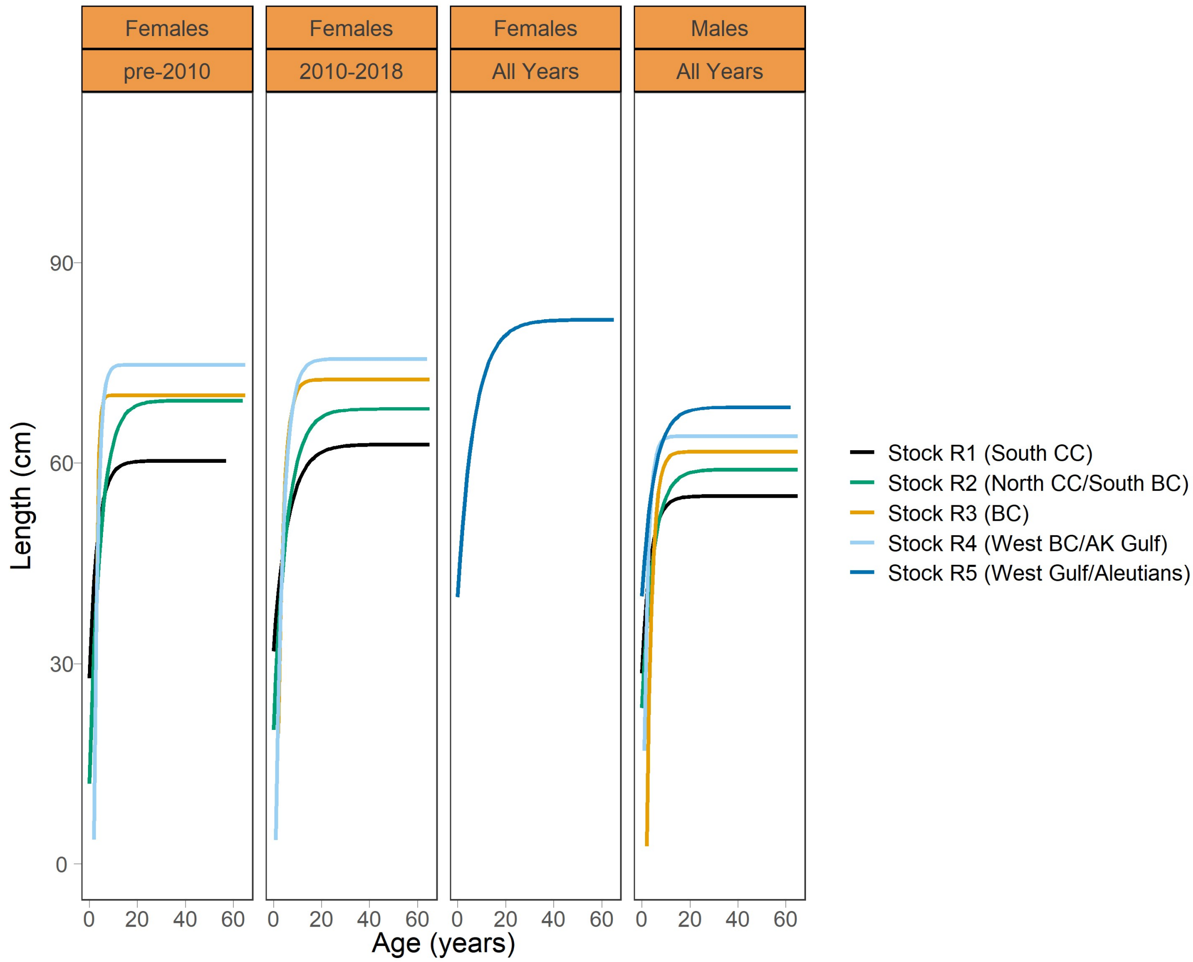

Figure 5. Input growth curves by stock. Stock labels correspond to light grey boxes in Figure 1.

Figure 6. Placeholder for input movement rates.

Figure 7. Placeholder for input landings.

Figure 8. Placeholder for input selectivity curves.

Figure 9+. Placeholder for comps, etc.

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